Chapter 11

Degradation Monitoring Systems for a BIM Maintenance Approach

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Additional information is available at the end of the chapter

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Abstract

Digitization allows to develop unprecedented technological systems based on the use of sensors, robotics, and automation. The construction industry is involved in this process of integrating new technologies through a platform called Building Information Modeling (BIM), which simplifies the management of the increasing complexity of construction processes. This methodology aims to create a global interactive system of information sharing between the different actors in the construction process. The integration of the processes creates economic and environmental opportunities, which can translate into increased efficiency of the sector. The information collected can be used throughout the construction lifecycle, which together with the monitoring of the buildings will support maintenance decisions. The monitoring of reinforced concrete structures with sensors allows the identification and quantification of the degradation processes, through the monitoring of several characteristic parameters of the reinforced concrete over time, and the determination of significant changes that indicate the existence of a degradative process in development. Obtaining this type of information, and its integration into BIM models, will allow intervention at an early stage in order to limit damages and costs associated with the maintenance of the structure, contributing to increase in the structure's useful life.

Keywords: concrete, monitoring, BIM, maintenance, innovative construction

1. Introduction

Industrialization has been a dynamic process that began at the end of the eighteenth century through the mechanization of manufacturing processes and which has extended to the present day. The initial phase of this process is called the industrial revolution for having introduced deep changes in the society at the time. Industrialization involved continuous progress, and also disruptive processes such as the electrification of the factory in the early twentieth century, called the 2nd industrial revolution, or automation using electronic and computer media that began in the 1970s (3rd industrial revolution) [1]. At present, we are going through the so-called 4th industrial revolution also known as digitization, which is characterized by the use of Cyber Physical Systems (CPS), based on heterogeneous data and knowledge integration [2], as shown in **Figure 1**.

These systems aim to respond rapidly to production requirements, which are subject to frequent changes, and to the improvement of industry performance in terms of efficiency and effectiveness [3]. The digitization will allow to create unprecedented technological platforms for consumer products systems, urban infrastructures, and industrial assets, based on the use of intelligent sensors, robotics, and automation [4]. The process of evolution that the industry was developing and implementing was formalized in Germany in 2013, with the presentation of the program called “Industry 4.0,” which involves digital data, digital access, automation, and connectivity. Subsequently, other countries presented their own industrial development strategies, the USA with the “Internet Industrial Project,” France with the “New French Industrial” strategy, England with the “British Industrial Strategy of 2050”, Japan with the “Revitalization Strategy of Manufacturing”, and China with “Made in China 2025” [5].

All these strategies seek to accelerate the integration of new technologies into production chains in order to improve their overall operation. The intelligent factory model, according to the Industry 4.0 concept, is based on the widespread use of ciber physical system, which allow the vertical integration of its various components to implement a flexible yet reconfigurable, though intelligent, production system. This type of factory, like any other factory, is equipped with physical objects (machines, conveyors, and products), and also with automation and information systems to implement flexible and agile production. In the Industry 4.0 concept, a factory consists of four levels of resources, which are the physical resources, the industrial network, the cloud, and the control and supervisory terminals. The former are equipped with intelligent systems that communicate with each other through the industrial network. The cloud supports the integrated information system, where the data obtained at the physical resources level are collected and processed and interact with the operators through supervisory control terminals [6]. Computational data processing techniques, usually called Big Data, allow the processing of large amounts of information, extracting useful results according to a specific objective [7].

Like all industries, the construction industry is also involved in this process of integrating new technologies and reformulating supply networks [8]. However, the construction sector

1st industrial revolution	2nd industrial revolution	1rd industrial revolution	4th industrial revolution
End of 18th century	Beginning of 20th century	Decade of 1970s	Today
Introduction of mechanical production	Industrial electrification	Automation of production	Cyber-physical production systems

Figure 1. Graduation scheme of the industrial revolution.

has specific characteristics that, a priori, make it difficult to adapt to these new technologies. Among these peculiarities is the fact that the construction process is temporary, unrepeatable (both in terms of content and location), phased, and involves a large number of actors with different levels of expertise. These variability and fragmentation constitute a challenge for the efficient coordination of projects, limit the possibility of learning from experience, make it difficult to implement a process of continuous improvement through repetition, and impose complex coordination of communication and exchange of information between stakeholders [9]. This sector is also characterized by having a very strong and rigid culture, which presents little openness to change [10]. A construction work can be analyzed in physical terms by the set of steps or processes that take place outside the work site, before starting and during its execution, the activities that take place at the construction site during the execution of the work, and later during the use phase of the construction.

To join all phases of a construction process, which involves the activities that take place before, during, and after construction, which are naturally linked, but which need a support that shows the whole process in a clear way, in order to be able to improve effectiveness and overall efficiency of the system. Most of the studies on Industry 4.0 consider the BIM methodology as the base technology for the digitization of the construction sector, by allowing the simulation and modeling of the constructions, which facilitates the management of the increasing complexity of the construction processes. On the other hand, this technology will allow in the future the integration of all the information produced from the design phase until the end of the life of the construction process [2].

2. Building information modeling (BIM)

The BIM methodology focuses on the creation of a global interactive system of information sharing between the different actors in the construction process [11]. This methodology allows to develop synergies in the various phases of this process, especially in the construction phase, and also in the design phase when critical issues need to be decided. Integrating the whole process creates important opportunities for reducing economic and environmental impacts and may in the future produce significant increases in efficiency in the construction industry, which is considered to be one of the least efficient industries [12]. This methodology aims to obtain a global view of buildings (and infrastructures), creating an information base that can be used throughout its life cycle, but that imposes changes in the way they are designed, constructed, and managed.

The BIM methodology is based on the use of a database infrastructure to incorporate the information about a construction according to the specific interest of the actors in the process, having as support the 3D modeling of the building. It integrates digital descriptions of all objects of construction and the interconnections between the different objects, so that those interested can consult the information, simulate the behavior, and estimate the activities and the processes of construction in a logical study of the life cycle [10]. This methodology leads to the development of the projects in a more interactive way among the different specialties, allowing to identify the design incompatibilities in an initial phase. The centralization of information optimizes the preparation of the work both in terms of measurements, budgeting, and preparation of the planning of the work.

In the work phase, the use of 3D modeling allows visualizing, both 2D and 3D, the works to be developed, facilitating their understanding and simplifying their execution. A study published by Hosseini et al. shows that interest in research on off-site construction has increased in recent years, focusing primarily on operations and management [13]. In this context, it is worth highlighting the use of the LEAN methodology as a management tool, as it promotes the reduction of waste in the production chain. This methodology focuses on identifying the products and services that have value for customers, with the objective of eliminating the parts that are not valued, classified as waste. It is a process that involves defining the value chain of the product, promoting the continuous flow of the product/service through the value chain (reducing production times and removing obstacles), seeking to produce exclusively what customers want (reducing stock), and promotes a process of continuous improvement, aiming to reduce the time of production cycles and obtain the best relation between quality and quantity, always focusing on the interest of the customer [12].

After construction, the information produced is available to the developer, so the process of maintenance and monitoring of the buildings is supported on a solid basis, which allows to support the decisions of interventions. This information can range from product datasheets to equipment manuals to enable service technicians to access specific equipment data for their interventions. In order for maintenance processes to be consistent, it is also important to monitor buildings in structural and environmental terms in order to collect information over time that will support maintenance and eventually end-of-life decisions.

The implementation of information modeling of buildings will contribute to the massive production of new data related to buildings, which will necessarily have to be treated as intrinsic value for the performance of the sector, will require the use of computational techniques for data processing, such as Big Data, which has applications for almost all industrial activities, including the construction industry. Currently, large volumes of heterogeneous data are already being worked on in the industry, which tend to increase exponentially as new systems are introduced, including sensor networks for data capture, which tend to increase user convenience [7].

3. Maintenance management tools

The maintenance of a building should be done using tools that allow the definition and implementation of clear guidelines to be able to develop the necessary maintenance actions. This activity can occur in three distinct but complementary forms, called preventive, corrective, and predictive maintenance, depending on its operationalization of a set of elements, namely:

- preventive maintenance action plans;
- issuance of work orders;
- recording of occurrences and failures;

- recording of actions taken for use in fault diagnosis;
- description of how the failures were identified;
- recording of possible causes (predictive capacity);
- resources made available and used;
- collection of relevant information (support for future events).

Preventive maintenance occurs in a planned manner, systematically with defined time intervals, or conditionally, depending on certain predefined conditions. The planning of interventions is supported in the prior knowledge of the durability characteristics of the materials and the specificities of the existing equipment in the building. It is sought to avoid the appearance of problems and, in this way, to limit the consequences that result from the normal deterioration of the materials. Preventive maintenance reduces operating costs, increases the life of buildings, and ensures user safety.

Corrective maintenance is the reaction to a certain occurrence, which may be urgent or not, whose purpose is to restore normal building use. This type of maintenance may involve high costs, both in terms of the materials and labor required to be mobilized, and costs associated with the discontinuity of the current use of the building.

The third type of maintenance is the predictive maintenance and results from the analysis of the information collected through the monitoring of the building and the inspections carried out. Predictive maintenance allows us to anticipate the need for maintenance services for a particular component of the building, contributing to:

- reduce corrective maintenance work;
- prevent the multiplication of damages;
- limit the impact of interventions on the use of equipment;
- extend the use of the different building components;
- mitigate the impact of inspections;
- increase the time of use of the building without constraints;
- raise the degree of confidence in the performance of the building.

For the development of models of predictive maintenance in buildings, it is necessary to use systems of measurement of relevant indicators, in a more or less continuous way in time. Through the use of the BIM methodology, it is possible to integrate these indicators in a single information system on the state of construction over time and, simultaneously, to have access to the basic information, as well as the characteristics of the materials used in the construction. This way, we can articulate the collected information with the pre-existing information in the 3D model of the building. In this way, it is possible to make a quick and efficient analysis of the state of the building [14]. Tools that link maintenance management to BIM models are in development. With this link, it is intended to facilitate the integration of data collected for maintenance management in BIM models, in order to automize, through algorithms, the production of maintenance service orders [15].

In the specific case of the maintenance of reinforced concrete structures, several indicators are used to measure their performance and can be used to measure the conservation status and determine the need to carry out predictive maintenance interventions.

These indicators aim to identify and quantify the degradation processes to which the reinforced concrete is subjected, measuring its variation over time, in order to determine at an early stage significant changes that indicate the existence of a degradative process in development. The obtaining of this type of information allows to intervene at an early stage in order to limit damages and costs associated with the maintenance of the structure, contributing to increase the useful life of the structure and give relevant information to increase the durability of new structures.

In general, the test methods are classified as destructive and non-destructive. The first type of methods can be used in laboratory tests, but they can hardly be used systematically in operating structures. The non-destructive, or less intrusive, test methods are more interesting because they allow to follow the evolution of the phenomena of degradation of the structures.

The first sensors for the monitoring of reinforced concrete appeared in the 1990s, among which can be distinguished the sensors consisting of two electrodes, one of black steel (anode) and the other of a noble metal (cathode), embedded in the concrete that confers protection against corrosion of the anode and through which the passage of electric current could be measured, as shown in **Figure 2**. These sensors are based on the principle that at an early stage, while the concrete presents a high pH, the passage of electric current is negligible or zero and, at a later stage, either by the effect of the carbonation front or the penetration of chlorides, the pH of the low concrete creates conditions for the corrosion of the anode and, simultaneously, for the passage of electric current between the electrodes, which will increase with the unwinding of the process of corrosion of the steel [16].

In the last decades, several techniques have been proposed and applied in the monitoring of reinforced concrete, and their integration in maintenance management systems has high potential. These monitoring techniques can be classified into five main categories, namely electrochemical methods, elastic wave methods, electromagnetic methods, optical detection, and infrared thermography.

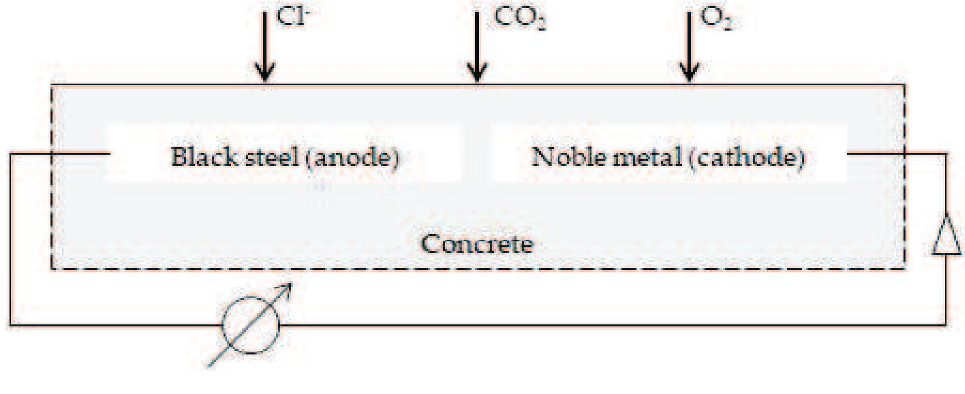

Figure 2. Sensor consisting of an anode in black steel and a cathode in noble metal.

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Electrochemical monitoring techniques include open circuit potential (OCP), concrete resistivity [17], linear polarization resistance (LPR) [18], galvanostatic pulse method (GPM), galvanic cell, electrochemical impedance spectroscopy (EIS) [19], localized electrochemical impedance spectroscopy (LEIS), electrochemical noise (EN), bar electrical resistance (BER), and surface potential survey [20].

The elastic wave methods include ultrasonic pulse velocity (UPV), acoustic emission (AE), and echo ultrasonic pulse (UPE). Among the electromagnetic (EM) methods, the most important are the ground penetration radar (GPR), surface penetration radar, X-ray radiography, computed tomography, and magnetic field disturbance.

In the field of optical detection are framed Bragg fiber optic networks (FBG). The last of the categories among the monitoring methods previously listed is infrared thermograph (IRT), which allows to identify defects in concrete structures, such as cracking or delamination.

4. Monitoring techniques

The monitoring of a reinforced concrete structure can be carried out by means of the acquisition of data with different periodicities. Embedded systems allow regular readings to be collected continuously over time. Non-embedded systems, which involve the intervention of an operator, tend to be used to collect punctual readings over the life of the structure. Embedded systems have the added advantage of being able to monitor both the visible areas and the difficult-to-access areas of the structures.

4.1. Electrochemical techniques

In the following sections, the main electrochemical techniques used in the monitoring of reinforced concrete are analyzed. The techniques presented allow more or less continuous reading of the respective variables.

4.1.1. Measurement of electrochemical potential

All materials tend to interact with the surrounding environment. In the case of steel embedded in concrete, this interaction occurs between the steel and the concrete surrounding it and

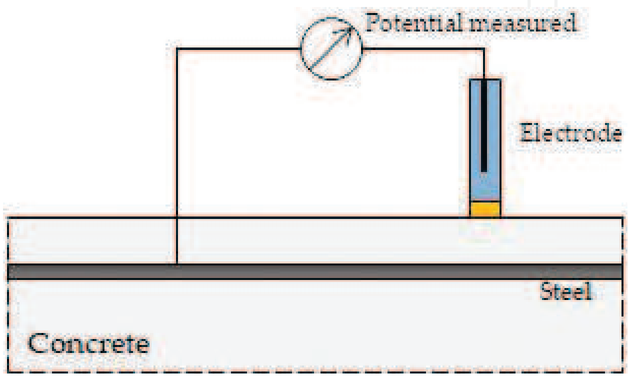

Figure 3. Measurement of electrochemical potential.

can be measured through the electrical potential of the reinforcement. The potential measurement allows estimating the corrosion state of the steel.

Potential measurement can be done through voltmeter, with high impedance, connecting the positive pole to the armature and the negative pole to a reference electrode. In embedded systems, the reference electrode is inserted in the concrete and is on the concrete surface in the case of portable systems, see **Figure 3**. In the first system, the connection to the reinforcement is made before concrete insertion, it being necessary that the steel is exposed to make the connection in the portable systems [21].

Measured potential less than −500 mV indicates that there is a high risk of the steel being corroded, the risk of corrosion being low when the potential is higher than −200 mV, according to **Table 1** [22].

4.1.2. Measurement of ionic resistivity of concrete

The ionic resistivity of the concrete has been used to determine the level of ionic contamination of the concrete, namely chloride ions, and the advance of the carbonation front. The ionic resistivity of a porous concrete depends, first, on the mobility and concentration of "free" ion, current carriers, in the solution that fills the porosity. Ionic mobility is an intrinsic characteristic of a chemical species varying only with temperature. That is, small ions, such as hydrogen, exhibit high mobility that increases with temperature. However, the "free" ionic concentration depends on the moisture content within the pores, the degree of contamination by external agents, and the solubility equilibrium of the different salts which may in the aqueous liquid fill the pores.

The resistivity of the concrete can be measured by using electrodes inserted into the concrete or placed on its surface. There are two main techniques, the two-electrode technique and the four-electrode technique. Both techniques have as presupposition the creation of an alternating or continuous electric field between electrodes. In the technique of the two electrodes embedded in concrete, the resistivity can be measured at various depths by creating an alternating electric field between the electrodes, usually in stainless steel, at the same depth, creating a current and measuring the potential difference. In the technique of the four electrodes placed on the surface of the concrete, the most common measurement process involves the creation of an electric field of alternating current between external electrodes and measurement of the potential between the inner electrodes [23], as shown in **Figure 4**. The following formula shows the relationship between the resistance measured by the electrodes and the resistivity of the concrete:

$$\rho = 2aR \tag{1}$$

with "a" being the distance between electrodes.

It is generally accepted that a concrete with a resistivity higher than 20 Ω cm is associated with a very low risk of corrosion of the reinforcement, and for that with a value smaller than 5 Ω cm, the risk of corrosion is very high, as shown in **Table 2**. There are, however, significant variations between the resistivity of concrete exposed to different environments, but the significant reduction of resistivity is an important indication of the risk of corrosion of the reinforcement [24].

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Potential of corrosion (mV)	Corrosion risk
$E_{corr} > -200$	Low (10 % risk of corrosion)
$-200 > E_{corr} > -350$	Intermediate corrosion risk
$E_{corr} < -350$	High (90 % risk of corrosion)
$E_{corr} < -500$	Severe corrosion

Table 1. Corrosion potential [22].

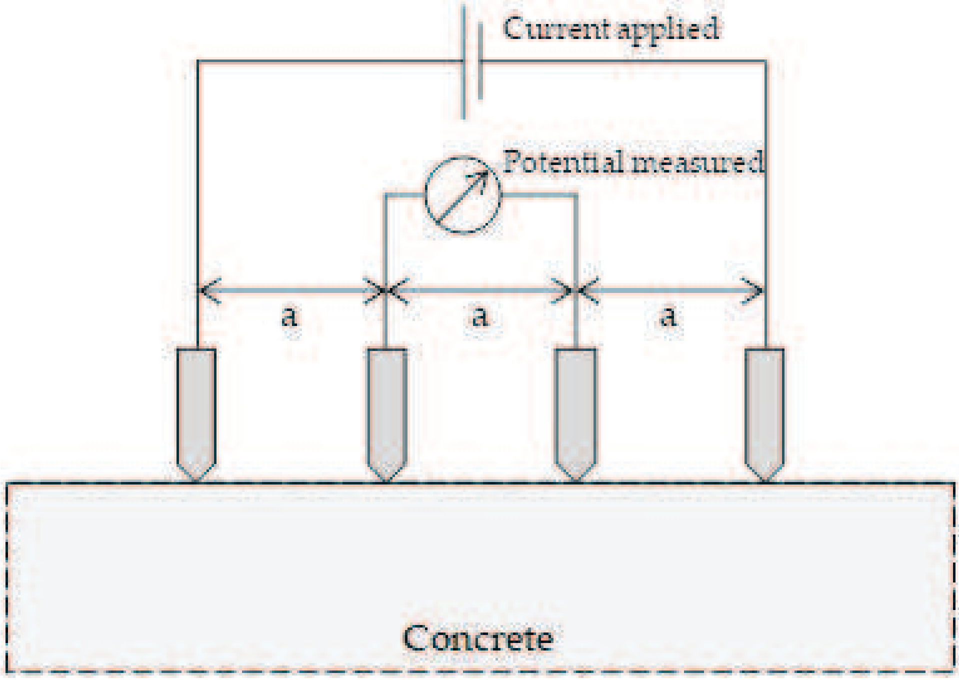

Figure 4. Technique of the four electrodes.

4.1.3. Linear polarization resistance

The polarization resistance (R_{pol}) can be defined as the slope of the polarization curve that results from the ratio of difference between the electric potential and the corrosion potential of the rebar, $E-E_{corr}$, and the intensity of the polarization current, I_E, so:

$$R_{pol} = \lim_{E \to E_{corr}} \frac{E - E_{corr}}{I_E} \tag{2}$$

The polarization resistance is related to the corrosion rate, i_{corr} (the density of the corrosion current that circulates between the anodic and cathodic zones during the corrosion process) through [25]:

$$R_{pol} = \frac{\beta_a \beta_c}{2,3 \ A \, i_{corr}(\beta_a + \beta_c)} \tag{3}$$

Resistivity (kOhm.cm)	Corrosion risk
R > 20	Negligible
20 > R > 10	Low
10 > R > 5	High
R < 5	Very high

Table 2. Ionic resistivity of concrete.

where *A* is the area of the rebar being inspected, and β_a and β_c are the Tafel parameters for the anode and cathodic processes, respectively. The coefficient $\beta_a\ \beta_c/2, 3/(\beta_a + \beta_c)$ ranges from 26 mV for active-phase corrosion reinforcement to 52 mV for passive reinforcement for corrosion [26, 27]. **Figure 5** shows a linear polarization resistance measurement sensor.

R_{pol} determination is made by varying the armature potential between −10 and +10 mV of the corrosion potential and recording the intensity of the electric current flowing between the reinforcement and the auxiliary electrode placed on the surface of the concrete. In addition to the auxiliary electrode, which imposes the desired potential on the rebar, it is necessary to use a potentiostat, which allows a constant and precise potential to be imposed on a robust and stable reference electrode, also placed on the surface of the concrete, in relation to which the armature potentials, the working electrode, will be measured. As can be seen from Eq. (3), the application of this method implies a thorough knowledge of the area of the armature section from which the polarization resistance is being determined [28]. **Table 3** shows the relationship between the corrosion current and the state of the steel.

The application of this technique can be done with a traditional three-electrode scheme (reference, work, and auxiliary), used in most systems, or with two equal electrodes.

4.1.4. Galvanic pulse

The measurement of the galvanic pulse is a technique that goes back to the beginning of the studies of corrosion of the metals and was also used in the first studies related to the

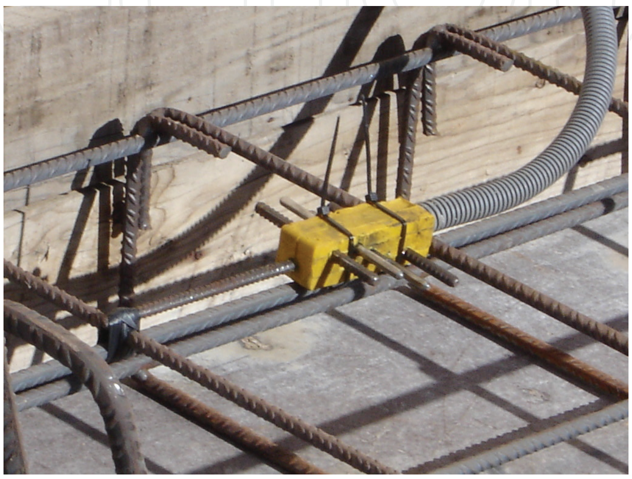

Figure 5. MoniCorr system for linear polarization resistance measurement.

Corrosion current (Icorr)	Condition of the rebar
Icorr < 0.1 μA/cm2	Passive condition
Icorr 0.1 - 0.5 μA/cm2	Low to moderate corrosion
Icorr 0.5 - 1.0 μA/cm2	Moderate to high corrosion
Icorr > 1.0 μA/cm2	High corrosion rate

Table 3. Corrosion rate.

concrete-steel interaction. The galvanic pulse method is based on the application of a transient bias current in a given period of time to the reinforcement inserted in the concrete. In general, a current between 10 and 100 μA with a duration of 10 s is applied [29]. In this way, the armature is polarized in the anodic direction and the potential of corrosion is compared, with the alteration of the electrochemical potential being compared with a reference electrode, which can be in stainless steel or titanium [30]. An example of a sensor for measuring the galvanic pulse is shown in **Figure 6**.

4.1.5. Electrochemical impedance spectroscopy (EIS)

The electrochemical impedance spectroscopy (EIS) is a non-destructive technique that allows to quantify the corrosion of the reinforcement inserted in the concrete. The impedance, Z, results from the relation between the voltage and the current intensity, for alternating current [31]. This technique is based on the assumption that an electric circuit can represent the behavior of the steel inserted in the concrete. Its application is based on the application to the rebar of a set of small alternating sinusoidal potential signals between 5 and 10 mV, the system response being measured in a current for a frequency range normally between 0.1 and 20,000 Hz. Impedance has one actual (Z') and one imaginary (Z'') component; the actual impedance component represents the resistive part of the system, while the imaginary component represents the capacitive part [24]. The representation of the direction and magnitude of the vector impedance for each frequency results in the so-called Nyquist diagram, **Figure 7**.

In the steel-concrete system, the most commonly used equivalent circuit is that which is also shown in **Figure 7**. The first RC network is intended to simulate the film or layer of iron oxide which forms on the surface of the steel when it is in contact with the concrete, and the second network, the behavior of the double layer. The same figure also represents the response of

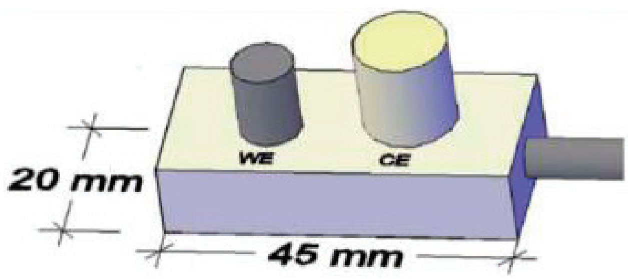

Figure 6. Galvanic sensor composed of steel and stainless steel [30].

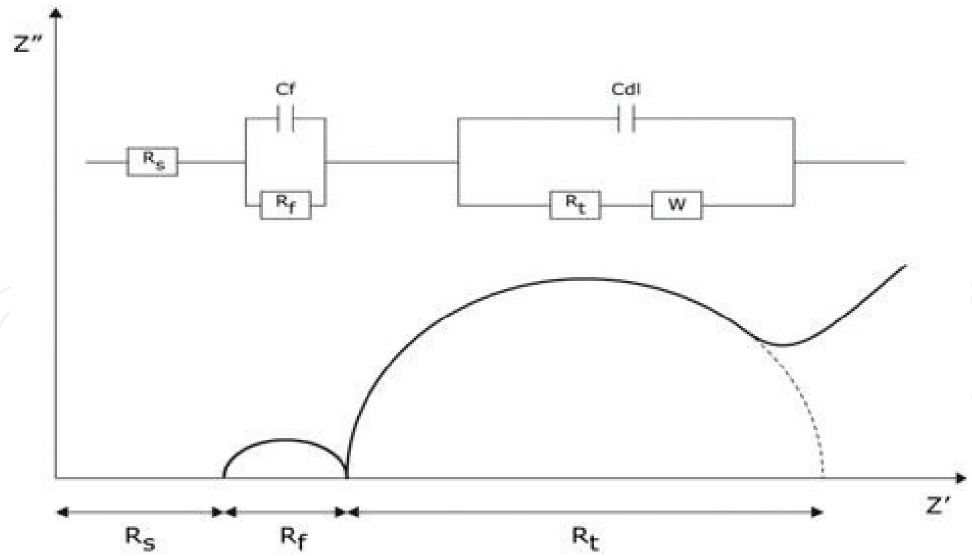

Figure 7. Equivalent circuit for the concrete-steel system and representation in the Nyquist diagram.

this circuit in the Nyquist diagram. In the Nyquist diagram obtained, the extrapolation of the diameter of the semicircle from the right to the Z′ axis allows the transfer value to be obtained at the load resistance which is equivalent to the polarization resistance used in the Stern-Geary equation and used in monitoring [32].

This technique allows to provide complementary information about the corrosive process of the reinforcement, as well as the dielectric characteristics of the concrete and the layer of oxide that forms on the reinforcements inserted therein. This technique also allows the measurement of the instantaneous corrosion rate (Rp) and the type of mechanism of the phenomenon—activation, concentration, or diffusion.

4.1.6. Electrochemical noise

Electrochemical noise measurement is a monitoring technique that can provide information on the mechanisms and corrosion rates of the reinforcement inserted in the concrete. This technique is based on the analysis of the variation of potential or current of low intensity, of the order of the microvolts, and allows to detect small variations of corrosion of the reinforcements [24].

The equipment used in this process is a micro voltmeter or a micro ammeter and a frequency analyzer that transforms the electrochemical noise as a function of the time in frequency through the Fourier transform, with the results presented graphically in the form of amplitude versus frequency [27].

4.1.7. Ag/AgCl electrode produced by immersion in sodium hypochlorite acid

For the detection of the presence of chloride ions in the concrete, Ming et al. [33] propose the use of a selective electrode of chloride ions produced by immersion of silver wire in sodium hypochlorite solution. This Ag/AgCl electrode is produced from silver wires with a diameter of 0.5 mm, connected with copper wires, the joint being sealed with epoxy resin, leaving an exposed area of 7.85 mm^2, which corresponds to a length of 5 mm. The silver wire is pre-treated, which included immersion in nitric acid (HNO3) for about 10 min, followed by immersion in anhydrous ethanol with vibration for 5 min. The finishing is obtained by immersing the yarn in an acid solution of sodium hypochlorite, resulting in a very dense coating of AgCl on its surface. The Ag/AgCl electrode is embedded in the concrete, its potential being measured in relation to a reference electrode, which in this case is SCE (saturated calomel electrode).

According to the authors, the Ag/AgCl electrode presents good reversibility, especially in solutions containing chloride ion. It should be noted that the temperature at which the electrode works is important because it influences the potential results. This electrode presents as advantages a low manufacturing cost, reduced dimensions, good performance, and robustness. **Figure 8** shows the schematic used to test this sensor.

4.2. Elastic wave methods

Measurement of waves in concrete structures can be done with external systems, such as ultrasonic pulse velocity or pulse tomography.

4.2.1. Ultrasonic pulse velocity test

The ultrasonic test is one of the oldest non-destructive methods to determine the state of the concrete, allowing information on its mechanical characteristics, homogeneity, and the existence of voids or cracks. This test is based on the measurement of the time elapsed between the emission of an ultrasonic pulse and its reception, known as the distance between the transmitter and the receiver, that is, it determines the propagation velocity of the ultrasonic pulse between two points [34, 35]. To perform this test, an ultrasonic device consisting of a transmission transducer and a receiving transducer is used. The transmission transducer produces a voltage pulse that propagates through the concrete, the signal being received by the receiving transducer. The device measures the time between the sending of the signal and its

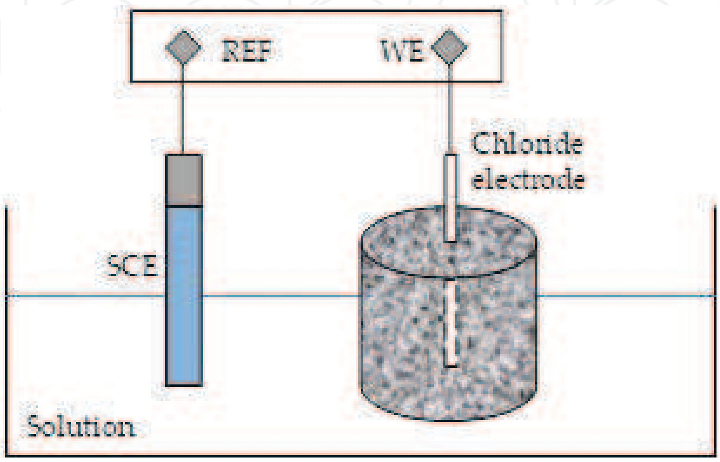

Figure 8. Ag/AgCl electrode embedded in the center of a specimen.

reception, determining the propagation speed of the wave. A small part of the emitted energy is reflected back to the surface. Wave velocity is reduced in areas where there are discontinuities. **Table 4** shows the classification of concrete as a function of ultrasonic propagation according to Whitehurst [36].

4.2.2. Ultrasonic pulse tomography

Ultrasonic tomography is a non-destructive inspection technique that allows mapping the interior of the structures and can provide reliable information about discontinuities or damage within the structures. This technique is based on the principle of reconstruction of the image with the evaluation of a series of projections of measurements made from different angles, that is, the real image of the object under study is estimated. The fidelity of this method depends on the process of acquisition and pre-processing of the data through mathematical methods of reconstruction. The generation of tomographic images can be categorized in techniques of filtered rear projection and iterative reconstruction [38].

The techniques of iterative reconstruction are based on the resolution of systems of algebraic equations generated from measurements, whose solution is a velocity map. By relating these data to the elastic characteristics of the materials, it is possible to detect discontinuities and damages in the elements being studied.

The authors [38] report that changes in compressive strength of concrete lead to different propagation velocities, with the velocity reducing with increasing resistance. In parallel, they concluded that the relatively uniform distribution of ultrasound velocities observed indicates that the tomographic technique for assessing the uniformity of concrete structures is adequate, and the analysis of the homogeneity of the concrete by ultrasonic tomography is more efficient than the simple analysis of velocity values of the waves. **Figure 9** shows a thermogram obtained by this technique.

4.3. Optical detection

Optical detection involves the installation of systems based on optical fiber, whose installation is generally carried out inside the structures, but can also be installed outdoors. In terms of reading, these systems allow continuous data collection.

Pulse velocity (m/s)	Quality of concrete
> 4500	Excellent
3500 a 4500	Good
3000 a 3500	Doubtful
2000 a 3000	Poor
< 2000	Very poor

Table 4. Classification of concrete quality based on the pulse velocity [36, 37].

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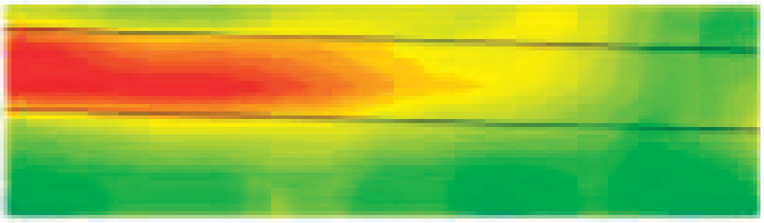

Figure 9. Thermogram obtained on the transducer at 250 kHz.

4.3.1. Fiber Bragg grating

Fiber Bragg grating (FBG) grid sensors can be used to monitor temperature, voltage, displacement, pressure, and, indirectly, corrosion. This type of sensor reflects at a given wavelength and transmits into another, producing a periodic variation of the refractive index of the fiber core by ultraviolet laser irradiation. The sensor itself, the Bragg grid, is a small segment of the core of the optical fiber exposed to ultraviolet light, which when actuated produces changes in the reflected wavelength. The reflected light corresponds to a specific wavelength, the light of the remaining wavelengths being transmitted through the Bragg grid [39].

Any deformation, whether by change in temperature, pressure, or vibration, applied in this grid alters the wavelength of the laser and changes in the magnitude of the reflections. These changes allow accurate measurements to be made, which can occur for long or extremely short periods of time, so that the quantification of the action on the sensor can be determined by the relation between the physical properties and the reflected wavelength of the FBG sensor [40]. **Figure 10** shows the operating scheme of an FBG sensor according to Kim et al. [41].

The unprotected FBG sensors are very fragile, so they need to be wrapped in a protective cap. The design of the capsule must be designed to allow the sensor to function and at the same time be protected. The shape and material of the capsules of the FBG sensors vary depending on the type of measurement desired and the installation site [42].

The FBG sensors have a set of characteristics that makes their use very appealing, among them being the insensitivity to the electromagnetic fields, the small size, and the weight, which make them suitable to be incorporated or fixed to any structure. Its connection to the exterior is effected by the optical fiber itself, which serves as a signal propagation channel for the control system. In addition, these sensors have excellent resolution and range, are immune to adverse weather conditions, and are resistant to water and corrosion [43].

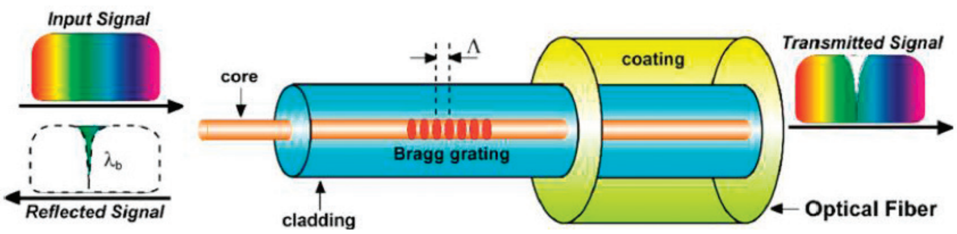

Figure 10. Operating principle of an FBG sensor [41].

FBG temperature sensors work on the basis of changing wavelengths in response to temperature changes. These sensors are protected by a small steel housing. The configuration of this transducer allows to keep one of its ends free, allowing the stainless steel rod to expand as a function of temperature variation, allowing the operation of the FBG sensor [44].

The voltage sensors work on the basis of the change in wavelength that results from the applied voltage, which produces elongation of the grid. These sensors are connected directly to the surface of the structure to be monitored, so as to have a deformation coupled with the deformation of the structure.

The displacement sensors estimate the deformation of the structure as a function of its deformation. These sensors allow you to measure the elongation, or shortening between the two points where it is anchored [44].

During the process of corrosion of the reinforcement, the volume of the rust produced is about four to six times greater than the volume of the original steel. With the reinforcement confined by concrete, this increase of volume introduces internal tensile stresses in the surrounding concrete, leading, when this tension exceeds the tensile strength of the concrete, to its cracking [45, 46]. Almubaied et al. studied the behavior of the FBG sensors installed on the face of the armature and concluded that the sensors have a good sensitivity to the progression of the corrosion process [47].

4.4. Infrared thermography

Infrared thermography is a monitoring and diagnostic technique that allows detecting superficial and internal anomalies such as voids, delamination, and cracks. This technique is based on the measurement of the surface heat transfer of a body, which occurs by radiation and conduction, by detecting the infrared radiation located in the region of the electromagnetic spectrum between the visible light and the microwaves.

Radiation is the mechanism by which a surface emits energy per unit area, which can be determined by Stefan-Boltzmann's law. Any object with an absolute nonzero temperature (−273.15°C or 0 K) radiates energy in the infrared region [48]. The factors that determine the level of the infrared radiation emitted by a material are the temperature of this material and its emissivity. The emissivity, which varies between 0 and 1, is a property of the material defined by the relation between the capacity of its surface to emit energy by radiation and the energy radiated by a black body whose emissivity is unitary ($e = 1$) due to the fact that possess null transmissivity and reflectivity. The emissivity of the concrete varies between 0.88 and 0.94 depending on surface roughness and moisture content.

The infrared camera produces a visual image from the conversion of the thermal radiation pattern of the surface under study [49]. This technology does not measure the temperature of the object under study, but identifies the different levels of radiation emission. The image obtained is influenced by the existence of other materials on the concrete surface, such as stains, water, or paints, which have different emissivities. The state of weather influences the results—if on the one hand the sunlight can increase the temperature of the surface, on the other the wind can decrease its temperature, such as rain. All these factors can contribute to

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highlight the temperature differences in the surface under study, allowing a better identification of the anomalies [50].

Thermography can be performed using the external heat source or natural heat source. In the first case, it is necessary to create an artificial thermal stimulus. In the second case, which is the approach suggested by the standard ASTM D 4788 [51], natural heat sources are used, with measurements being taken during the day and at night, to obtain images of thermal flows into the interior of the concrete and reverse heat flows, respectively, as shown in **Figure 11**.

Standard ASTM D 4788 [51] defines the criteria to be applied in determining the delamination of trays of reinforced concrete bridges through the use of infrared thermography. A number of authors have explored the use of this technology, namely Clark et al., who were able to identify delaminations in bridge trays with diameters less than 20 cm [50], and Cannard et al., who have been able to identify defects with areas of about 4 cm^2 [52]. More recently, Caldeira et al. used this technology to identify adhesion damages between concrete and reinforcing strips in glass fiber-reinforced polymers (GFRPs) [53]. In this study, several external heat sources were used, namely incandescent lamps, high-pressure sodium lamp, and convection heater, and concluded that the type of heating influences the quality of the thermographic evaluation and the uniformity of the heat flow in the samples.

With the proliferation of drone technology, the use of unmanned aerial vehicles to obtain thermographic images has arisen. Omar et al. have studied this technology and have identified as an immediate advantage its ability to allow the circulation of vehicles during the tests, which is extremely interesting in areas of heavy traffic and for allowing inspections to be carried out more frequently, according to the needs. This technology will also allow the expansion of the number of inspected structures, due to the time saved and the associated cost reduction. This type of technology is an important tool for the management of maintenance processes, since it allows assessing the conditions of the bridges at various stages of their useful life, contributing to the collection of supplementary information, which will allow to base the decision making regarding operation maintenance. Although most of the studies focus on the evaluation of the reinforced concrete bridges, this technology can also be used in the other components of the bridge [48].

4.5. Radio frequency identification systems

Radio frequency identification systems, other than sensors, can be very interesting support elements for a multifunctional maintenance system. These systems, usually referred to as RFID (radio frequency identification), consist of a reader connected to an antenna, which

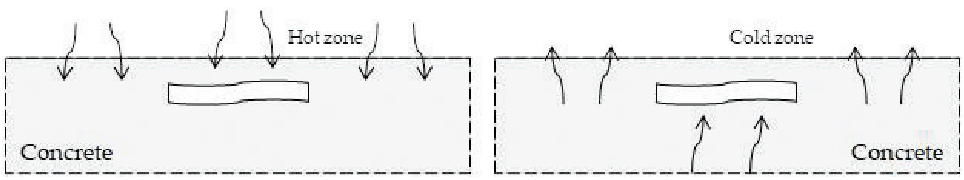

Figure 11. Effects of an interior anomaly on surface heat flux.

allows detection and reading of labels with stored information. These tags are composed of an integrated circuit and a small encapsulated antenna [54]. A computer, connected to the reader, manages the system through a suitable application [55].

The antennas can identify the labels at different distances according to the intended purpose, with systems that allow reading at small distances, a few centimeters, to systems that allow reading at greater distances, up to about 100 m. In order to choose the type of labels to adopt, its capacity of storing data and the position in which it will be placed on site is relevant. The frequency of operation of the devices depends on several parameters, namely the need to modify the contents of the labels, protection of the privacy of the data, the materials used, or the portability of the reader [54].

After construction, RFID systems can also be used to make the work of maintenance teams more efficient, through their installation in the various equipment that will be the object of maintenance throughout the life of the construction, allowing to monitor their condition or performance. According to Cheng et al., these devices may also be incorporated during construction into materials or structural elements, storing information. This would allow transferring data from the design phase to the maintenance phase, leading to the building itself providing data, increasing the efficiency of the maintenance system [56].

4.6. Analysis of monitoring techniques

For the implementation of the monitoring of a structure, it is possible to use sensors embedded in the concrete, with the readings being taken with certain periodicity, or by the use of equipment that allows obtaining punctual readings through the contact with the surface of the concrete, of singular use. For some of the techniques there are two possibilities, such as the measurement of resistivity either by sensors embedded in the concrete or by the method of the four external electrodes. **Table 5** presents the type of use for each of the techniques.

The monitoring techniques presented have been tested, in recent years, in the laboratory, and also in real structures. Most of the studies focus on the importance of using two or more techniques simultaneously, in order to guarantee a high level of reliability in the analysis of the results. This type of system has been installed in numerous real structures, some of which we mention:

- Madeira Airport and the D. Henrique bridge, whose installed systems allow to measure the galvanic current intensity, resistivity, temperature, and corrosion potential [57];
- Alto Ceira Dam, where the deformation of the concrete, the movement of the joints, and the temperature are monitored using fiber optic sensors [44];
- Bridge, infrared camera monitoring installed on drones [48].

From the standpoint of maintenance, embedded systems have the advantage of providing information on the behavior of a particular variable over time. These systems can be installed in areas difficult to access after completion of construction, such as foundations or buried walls. Monitoring with embedded systems should not inhibit the use of external equipment as the sensors do not allow coverage of the entire surface of the structure. Thus, along with

Monitoring Techniques	Sensors embedded	External sistem
Electrochemical techniques		
Measurement of electrochemical potential	X	X
Measurement of ionic resistivity of concrete	X	X
Linear polarization resistance	X	X
Galvanic pulse		X
Electrochemical impedance spectroscopy	X	
Electrochemical noise		X
Ag/AgCl electrode (sodium hypochlorite acid)	X	
Elastic wave methods		
Ultrasonic pulse velocity test		X
Ultrasonic pulse tomography		X
Optical detection		
Fiber Bragg Grating	X	
Infrared Thermography		
Infrared Thermograph		X

Table 5. Monitoring techniques.

the use of sensors, regular inspections should be carried out to detect any undetectable degradations with the installed systems, and spot inspections resulting from the information collected during monitoring. The integration of information into a 3D model, which incorporates construction information, facilitates the detailed analysis of detected degradations. The use of information identification and storage tags (RFID) embedded in structural elements facilitates access to data during inspections and increases their effectiveness.

5. Conclusions

Digitization and automation will drive the construction industry to a new level of efficiency, eliminating non-fundamental factors. In the area of building maintenance, the BIM methodology will be the hinged element of this development process, through which it will be possible to progressively integrate new work tools. This integration will have a very large impact on plant management costs, which correspond to more than 65% of the building's operating costs.

The implementation of maintenance management systems, using reinforced concrete monitoring sensors, integrated in the BIM process, involves the use of 3D models, monitoring systems, and their interconnection interface. Of these three components, the development of the interface involves relatively low costs when compared to the costs of the BIM model developments and the installation of the monitoring system. This process will have a strong impact in reducing the time spent searching for information for the implementation of maintenance tasks.

From the point of view of the suitability of the systems for their integration into BIM, the monitoring of corrosion potential, ionic resistivity of the concrete, and polarization resistance can be distinguished by the experience of use and reliability of use. These electrochemical techniques along with the fiber optic solutions give assurances of operation to the systems.

For maintenance, the existence of these new information management models will facilitate the introduction of automated monitoring systems, encouraging the use of sensors, as a result of increasing the capacity to accommodate and organize the collected information. As a result, it will be possible to acquire and manage a greater volume of information, in a continuous way in time and without human intervention. This automation process is of interest to the entire building management system, since it allows managing the environmental variables (temperature, humidity, air renewal, etc.) of the different spaces, controlling the operation of the various installed equipment or measuring and analyzing relative indicators on the conservation status of structural or non-structural elements.

The structural monitoring systems presented can be integrated as maintenance management tools into 3D models. Its incorporation in the BIM methodology has the additional advantage of allowing, in a more intuitive way, the interpretation of results using the spatial location of each of the sensors. The results of the monitoring of construction in operation demonstrate the interest of the data obtained for the maintenance processes and emphasize the necessity of the conjugation of the reading of two or more parameters, in order to guarantee a high index of reliability of the system.

Future owners will want integrated, structured, and easily accessible information for their buildings. This intent will only be gain with the use of information and systems platforms.

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Conflicts of interest

The authors declare no conflict of interest.

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